
9. Seismicity associated with Longwall coal mining

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SYNOPSIS. Mining seismicity, and the related phenomenon of rock bursts, occurs throughout the world in association with the mining of coal, gold and other ores. Mining seismicity has occurred with magnitudes as great as 4.5 (South Africa), 4 (Poland) and 5 (Canada) and therefore constitutes a potential hazard, especially since focal depths are shallow. In Britain mining seismicity has been reported in several coalfields with magnitudes as great as 3.5. Various rock failure mechanisms have been identified. In this paper mining seismicity case studies from the North Staffordshire and South Wales coalfields are reported. Pillar failure, due to the super-position of stresses from active mining on residual stresses from previous workings, is responsible for the larger magnitude events, and presents the greatest seismic hazard.

INTRODUCTION

1. Seismicity associated with the extraction of coal, gold and other ores is a relatively common phenomenon occurring throughout the world, and in many of the reported case histories a direct casual relationship has been established between mining and seismicity. The seismicity is almost always associated with the occurrence of rock bursts during which rock in the vicinity of the mine excavation fails rapidly resulting in the sudden release of stored strain energy and the violent expulsion of rock from exposed faces. The occurrence of rock bursts during mining (ref. 1), which can cause significant damage to faces and roadways and fatalities has provided the main incentive for mining seismicity studies. However mining seismicity is also sometimes associated with the occurrence of earth-tremors of sufficient magnitude to be felt extensively at the surface. In South Africa and Canada, earth-tremors of maximum magnitude 4.5 and 5 respectively have been associated with mining (refs 2-5). Mining therefore can generate a significant seismic hazard. In Table A the occurrence of mining seismicity around the world is summarized together with estimates of the maximum magnitude and its nuisance potential. The potential for surface damage arising from mining seismicity is often enhanced since mining areas are frequently industrialized, corresponding to population concentrations,

COUNTRY	MATERIAL MINED	ROCK BURSTS	ENVIR. NUISANCE	MAX M.
S. AFRICA	GOLD	/	/	4.5
U.S.A.	COAL	/	?	4
U.S.S.R.	COAL	/	?	?
POLAND	COAL	/	/	4
U.K.	COAL	/	/	3.6
CANADA	GOLD	/	/	4.5-5
INDIA	GOLD	/	?	4
CZECHOSLOVAKIA	ZINC ORE	/	?	2.8
GERMANY	COAL	/	?	?
JAPAN	COAL	/	?	?

TABLE A

and because the focal depths are shallow, lying at or above the level of the mine workings.

2. For rock bursts and their associated seismicity mining activity is usually responsible for both the initial generation of the stored elastic strain energy and the release of this stored energy by brittle failure to generate the seismicity. However not all mining seismicity may be related to mining in such a way. In Silesia, Poland, although rock bursts wholly generated by mining do occur, seismicity extensively felt at the surface has been attributed to the release of natural stored strain energy by the mining process (refs. 6,7). Similarly in Utah, USA, the relationship between mining and adjacent seismicity is in part tectonically controlled, although some seismicity can be directly attributed to mining (refs 8,9).

3. In Britain rock bursts and mining seismicity are associated mainly with coal extraction. The following rock failure mechanisms have been identified.

- (a) Failure of rock and coal in the working area on faces or roadway sides e.g. South Staffordshire during 1930's (ref. 10).
- (b) Pillar collapse between workings e.g. Barnborough (ref. 11) and Hickleton - main colliery (ref. 12) in the Yorkshire coalfield.
- (c) Pillar and abutment collapse remote from the active face e.g. North Staffordshire coalfield (refs 13,14)
- (d) Activation of old fault planes due to adjacent mining activity e.g. North Staffordshire coalfield (refs 14,15).
- (e) Outbursts of gas and coal during the working of anthracite e.g. Cynheidre colliery, South Wales Coalfield (ref. 16).

4. Seismicity of sufficiently large magnitude to be felt at the surface has been experienced in the North Staffordshire, Yorkshire and Midlothian coalfields (refs 13,11,17) and has been attributed to mechanisms (b), (c) and (d). In this paper seismicity associated with longwall coal mining, the main coal extraction method used in British mines, is described and compared for mining seismicity case studies in the North Staffordshire and South Wales coalfields.

MINING SEISMICITY IN THE NORTH STAFFORDSHIRE COALFIELD

5. Small earth-tremors, associated with coal mining have occurred throughout the last century in the North Staffordshire coalfield. On 15th July 1975 a large earth-tremor was felt over an extensive area of Stoke-on-Trent. This had a magnitude, m_b , of 3.4 (as determined by the Institute of Geological Sciences Lownet seismometer network) and a maximum Mercalli Intensity of VI, and was the largest of a swarm of tremors which had been felt throughout early 1975 and continued to be felt until August 1977. During this period some 55 events were felt at the surface. This seismicity caused considerable concern to many people; the epicentral area being within the southern part of the Stoke-on-Trent conurbation. The seismicity was shown to be generated by the active mining of coal.

6. During the time that this seismicity occurred the epicentral area was being mined in the Ten Feet seam at a depth of 900 m below the surface. This area had previously been extensively extracted in the Moss, Bowling Alley, Rowhurst and Great Row seams and these earlier workings, especially those of the Moss seam, played an important part together with the active Ten Feet seam workings in generating the seismicity. A plan view of the Ten Feet seam workings and the earlier workings in other seams is shown in figure 1. The Ten Feet seam was extracted using the longwall mining method with total caving; the height of the extraction was approximately the seam thickness (2.4 m), and the face width was between 150 and 200 m. The geological sequence in the mined area consists of numerous coals occurring in a typical cyclical sequence with mudstone roofs and floors and occasional intervening sandstones (ref. 13). The dip is 8° to the South. The Ten Feet panels under extraction were situated between two major faults; the Newcastle and Apedale faults.

7. In response to the public concern, the Department of Geology, Keele University, in collaboration with the Global Seismology Unit of the Institute of Geological Sciences were commissioned by the National Coal Board to undertake a study of the seismicity in order to determine the cause. Seismic activity was monitored for 2 years using a 6 component seismometer network deployed in and around Stoke-on-Trent (ref. 13) and during this time panels 205 and 206 were extracted in the Ten Feet seam. The seismicity is shown in figure 2 together with the position of the Ten Feet panels, previous workings and faults. Plan and vertical sections are shown.

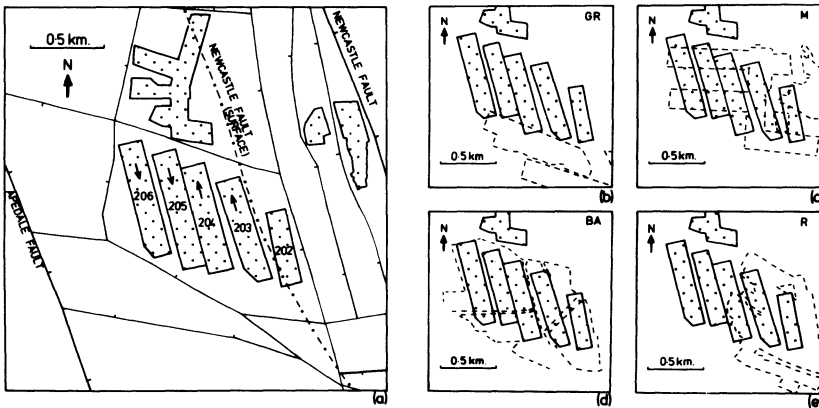


Figure 1

(a) Ten Feet seam panels 205 and 206 and faults at Ten Feet seam datum. Old workings in (b) the Great Row seam, (c) Moss seam, (d) Bowling Alley seam, (e) Rowhurst seam are also shown.

The tremors lie in close proximity to the active mine workings, mainly between the depths of 400 and 1000 m. The vertical E-W section shows that the seismic events do not lie along the Newcastle fault, although the workings are under the fault.

8. For one month during the mining of panel 206 a small aperture seismometer network was placed above the panel and used to augment the data of the larger network (ref. 14). The seismic events occurring during this month are shown in figure 3 on a N-S vertical section. These events have a higher accuracy of location (± 50 m) compared to the events of figure 2 and show a smaller depth scatter. From first motion analysis on these events both implosional and shear source mechanisms were identified. The implosional sources were found to correspond to the smaller magnitude events while the shear sources had larger magnitudes and were those felt at the surface. The shear events were mainly located in the pillars left between the Old Moss workings.

9. Analysis of the relationship between the hypocentres and the position of the face (ref. 13) showed that the events occurred just in front of the face and moved forward with the face. This suggests that the front abutment pressure played an important part in generating the events. The larger shear events within the Moss seam pillars occurred when the Ten Feet seam face passed under the pillars and were generated by shear failure triggered by the interaction of the Ten Feet front abutment pressure with the residual Moss pillar stresses

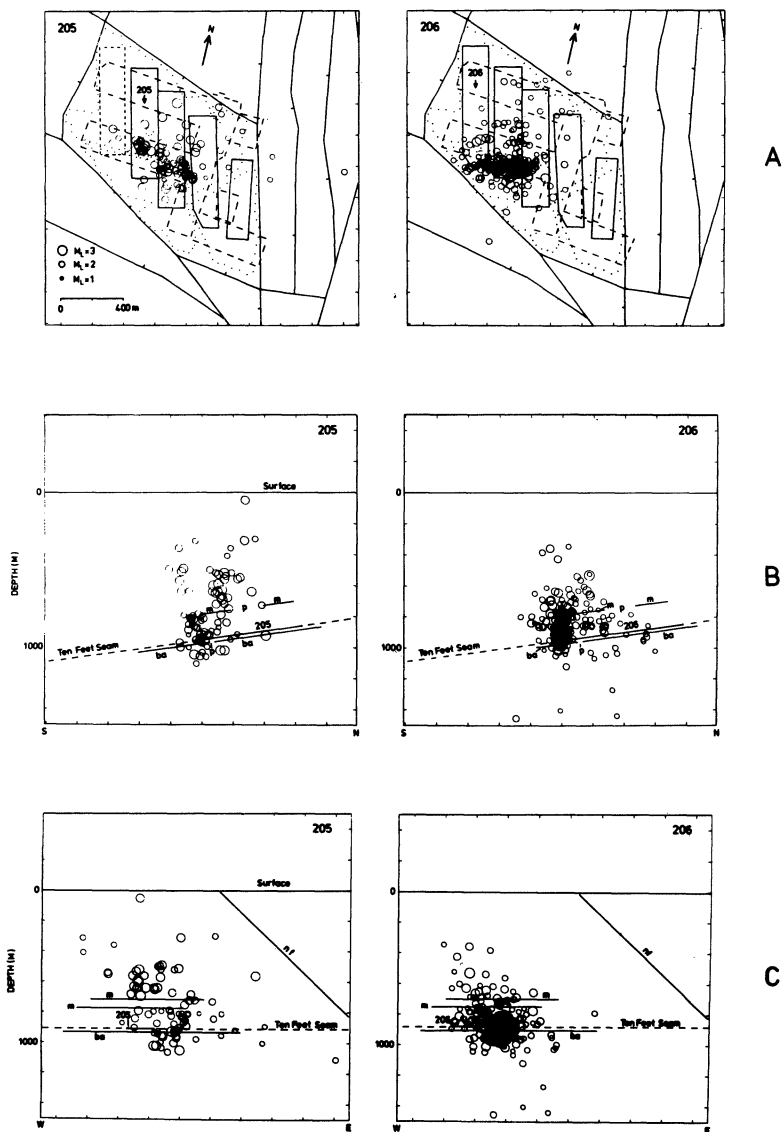


Figure 2
Tremor hypocentres occurring during the mining of panels 205 and 206 of the Ten Feet seam.
A) Plan view
B) Vertical section parallel to face advance direction
C) Vertical section parallel to face.
Old workings in the Moss and Bowling Alley seams together with faults at the Ten Feet seam datum are shown.

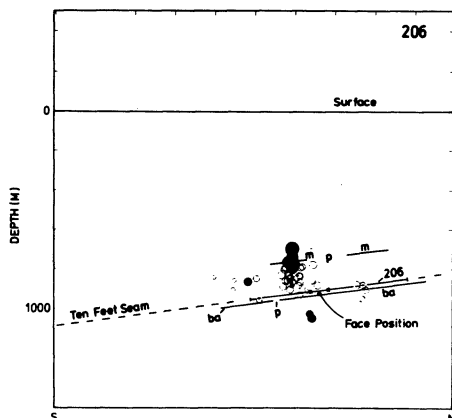


Figure 3

Vertical section parallel to the direction of face advance showing higher accuracy tremor locations for one months mining of panel 206. Open circles represent implosional source mechanisms - solid circles, shear mechanisms.

(ref. 14). In contrast the smaller implosional events occurring mainly at the level of the Ten Feet seam were most probably caused by waste collapse behind the advancing face (ref. 14).

10. Examination of the seismicity by day of week for tremors occurring during the mining of panels 205 and 206 (figure 4) showed that most seismic activity occurred through the working week falling between Monday and Friday. Seismicity at the weekend was much reduced and corresponded to no mining activity.

11. In figure 5 frequency-magnitude relationships are shown. The frequency-magnitude relationships follow the relationships

$$\log(N) = 3.18 - 0.61 M_L \text{ for panel 205}$$

$$\log(N) = 4.61 - 1.19 M_L \text{ for panel 206}$$

12. The magnitude distribution has been examined using Gumbel's third statistical distribution (ref. 18), and upper magnitude levels of 3.20 and 3.25 were predicted for panels 205 and 206 respectively. These values are only slightly greater than the maximum measured.

13. During the monitoring period 1975-1977 seismicity associated with mining was located elsewhere in the North Staffordshire coalfield. The seismicity together with the active mine workings is shown in figure 6. None of the seismicity was felt or exceeded magnitude, M_L , 2.5.

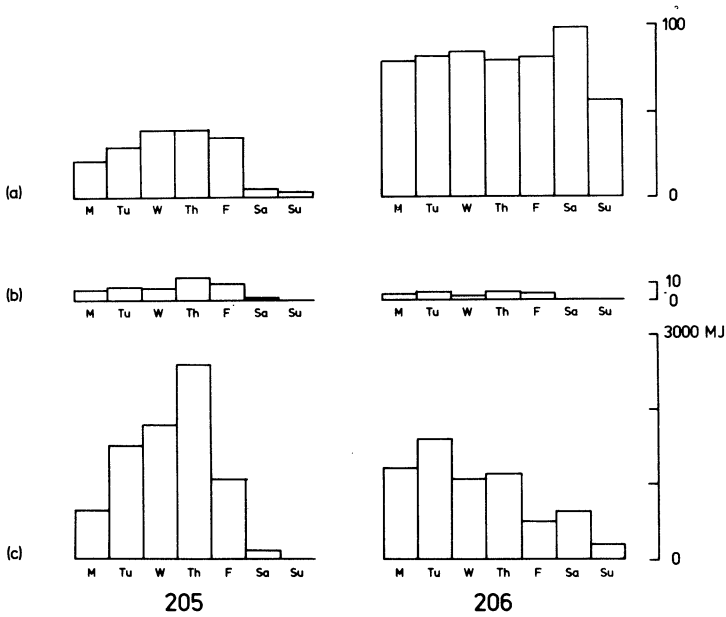


Figure 4

Histograms of cumulative number of tremors per day of week for panels 205 and 206

- (a) All located events
- (b) Felt events only
- (c) Total seismic energy

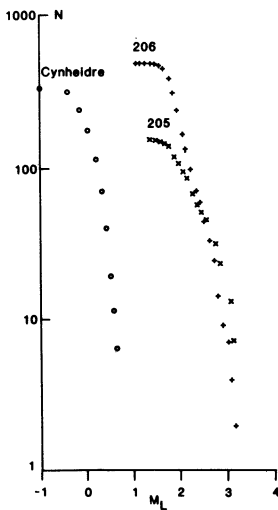


Figure 5

Frequency-magnitude relationships for tremors generated by mining of panels 205 and 206 of the Ten Feet seam, North Staffordshire and by mining at Cynheidre colliery South Wales Coalfield. Each relationship corresponds to mining over a similar time period.

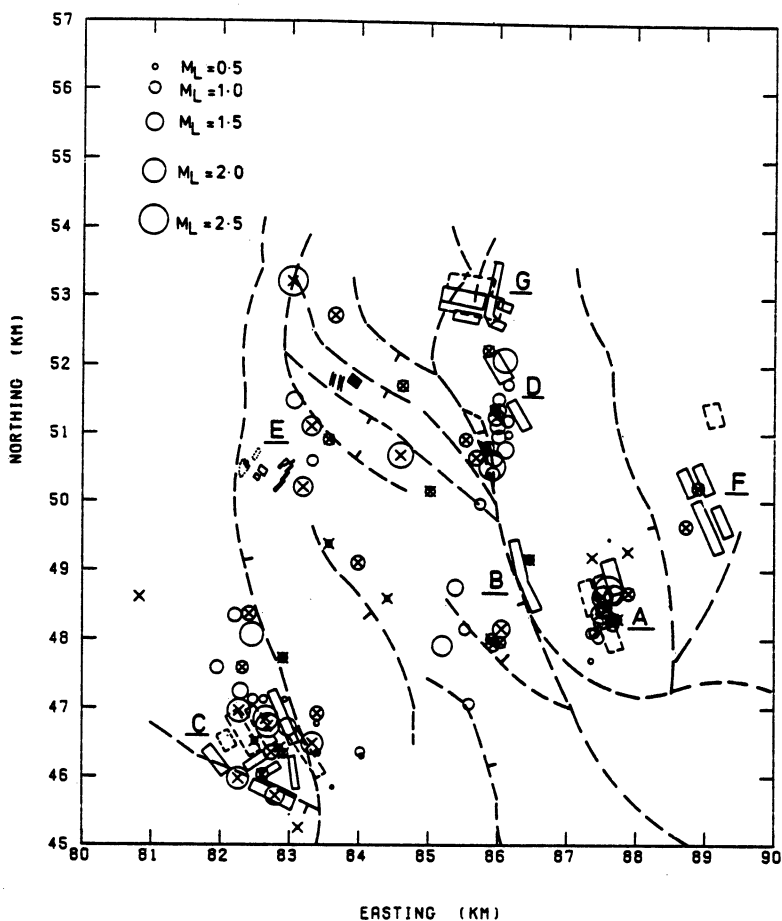


Figure 6

Tremors occurring in the North Staffordshire coalfield during 1975-1977 together with active mine workings. Open circles represent implosional source mechanisms - circles with crosses, shear mechanisms.

Seismicity in areas A, C and D was shown to have a similar mechanism to that of panels 205 and 206 of the Ten Feet seam; the seismicity again being generated by the interaction of active workings with pillars in old workings. In area B the seismic activity is thought to have been generated by subsidence induced slip as a pre-existing fault plane. During 1980-81 the seismicity of areas A and E increased in magnitude (maximum magnitude, 3.6) and was felt extensively (ref. 19). The mechanism responsible for the seismicity in area E is not known; it is not associated with active mining. The epicentral area for E is however underlain by old mine workings in a large number of seams.

MINING SEISMICITY AT CYNHEIDRE COLLIERY, SOUTH WALES COALFIELD

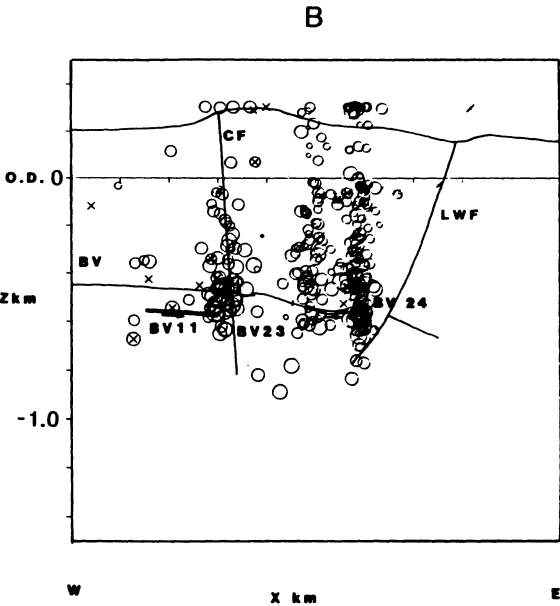
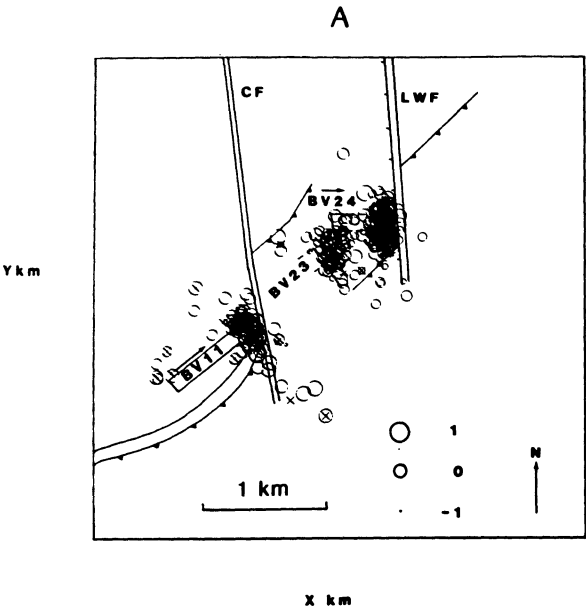
14. Seismic activity was investigated (ref. 20) at Cynheidre colliery* with the principle objective of studying activity associated with active longwall coal mining in a situation where there was no interaction with previous mine workings. This is in contrast to the Stoke-on-Trent mining seismicity case history where the active mining was in an area extensively mined in seams above and below the active panel. None of the seismicity at Cynheidre was felt. A subsidiary objective of the Cynheidre monitoring program was to seek seismic precursors to outbursts of coal and gas which have caused a number of fatalities and present a severe production problem at Cynheidre.

15. Cynheidre colliery, lying some 15 km north of Llanelli, is situated in the western most part of the South Wales coalfield and produces anthracite at depths up to 900 m below surface from seams within the Lower and Middle Coal Measures. The coal measures are here also typical cyclothem delta deposits with sandstones comprising about 10% of the total. The geological structure (ref. 20) of the area is extremely complex owing to the close proximity of the Variscan front. As a consequence the coal seams are within variably dipping strata frequently interrupted by both thrust and normal faults.

16. Seismic activity was monitored in the Cynheidre area for 9 months between January and September 1983 during which time mining of the Big Vein seam occurred in 3 panels; BV24, BV11 and BV23. The majority of the seismicity occurred in the immediate vicinity of the active coal workings. Plan and vertical sections showing seismicity together with the active panels' layout, the Big Vein seam and faults are shown in figure 7. Seismicity clusters around the 3 active panels and is largely restricted to depths shallower than 1000 m below surface. The greatest number of events and released energy occurs at a depth of 0.5 km below OD, corresponding to the depth of the active coal extraction. The locations have an accuracy of ± 50 m.

17. The existence of the 3 distinct clusters of events at the location of the three active panels indicates that this activity is related to the coal extraction. Levels of activity in each of these regions varied considerably throughout the monitoring period corresponding to variations in the mining

*commissioned by the Department of Environment



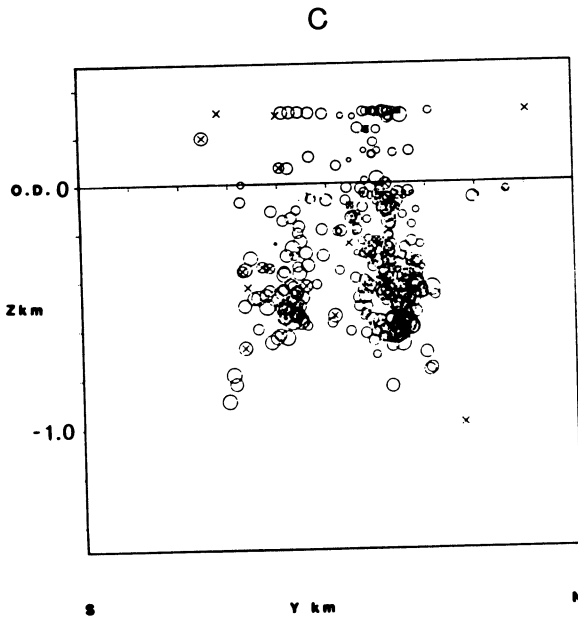


Figure 7

Seismic hypocentres located during the monitoring period February-September 1983 in the vicinity of Cynheidre colliery. Major faults and the location of the active panels are shown. Crosses are events of undetermined magnitude. C.F. Coalbrook Fault, L.W.F. Llety-Wilws Fault.

A) Plan

B) Vertical section (E-W)

Vertical Exaggeration 2:1

C) Vertical Section (N-S)

activity of each area and the geological structure. The activity of BV23 was associated with development work only.

18. Seismicity associated with panels BV24 and BV11 is shown in figure 8 where event hypocentres are plotted relative to the position of the moving face of each panel. Plan and vertical sections are shown; the vertical section being parallel to the direction of face advance. The position of the face is marked with a cross. Plan views show that for each panel the seismicity clusters within approximately 100 m of the face (the loose cluster of events in the bottom left quadrant of figure 8(a) is associated with BV23). The seismicity has also been shown to move forward in unison with the face (ref. 20). Vertical sections show that the majority of the events are distributed between the level of the face and the ground.

19. The seismicity associated with panels BV24 and BV11 is most probably caused by rock failure in the region above and in advance of the face, induced by the front abutment pressure. In the case of panel BV24 this panel worked towards, and came close to the Llety Wilws fault. This may have induced some failure on the fault or differential subsidence across it, although there is no direct evidence for this. Some of the observed seismicity behind the face may be caused by waste collapse. Focal mechanism studies show both shear and implan-sional source mechanisms.

20. The seismicity described in figures 7 and 8 lies in the magnitude range $M_L = 1$ to -1 . The frequency-magnitude relationship for the whole of the mining related seismicity occurring during the 9 month monitoring period is shown in figure 5. Although this curve has been conventionally modelled as a straight line for both natural and induced seismicity no such relationship is evident in figure 5. This may be due to the mixing of three distinct sources, or the event selection procedure.

21. The mining of anthracite at Cynheidre colliery is occasionally interrupted by violent outbursts of gas and suspended coal dust from the face or headings. These present a serious hazard to life and considerable interruption to the production schedule. During the monitoring period 4 outbursts occurred on BV24; 2 spontaneously and 2 induced by shot firing on the face. The occurrence of these outbursts does not relate in any obvious way to the seismicity already described in the magnitude range $M_L = 1$ to -1 . In figure 9(a) a seismogram of one of the outbursts is shown, recorded on the surface immediately above BV24. The outburst itself lasted about 20 seconds and was preceded by a number of very small events for which there is an increase in frequency of occurrence prior to the outburst until they become indistinguishable from each other. The outburst itself appears to consist of a large number of these smaller events which are estimated to have a magnitude less than -1 . In figure 9(b) a histogram of the number of these very small events occurring per 20 seconds, plotted against time for the two spontaneous outburst is shown. A clear increase in the activity level at these low magnitudes ($M_L < -1$) can be seen

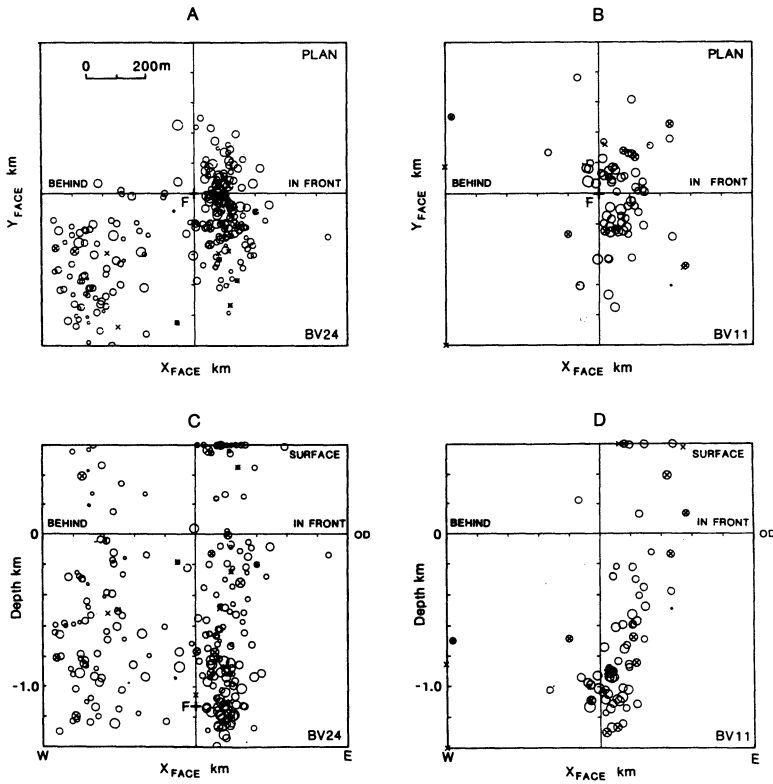


Figure 8

Seismic events associated with panels BV24 and BV11 at Cynheidre Colliery plotted in the coordinate frame of the advancing face. The cross at F marks the mid-face position. Other crosses are events of undetermined magnitude.

- A) Plan, BV24. Events in the south east quadrant relate to BV23
- B) Plan, BV11
- C) Vertical Section, (E-W), BV24, parallel to face advance direction. Events behind face relate mostly to BV23.
- D) Vertical Section, (E-W), BV11, parallel to face advance direction.

EARTHQUAKE ENGINEERING IN BRITAIN

OUTBURST 3.5.83 CH11

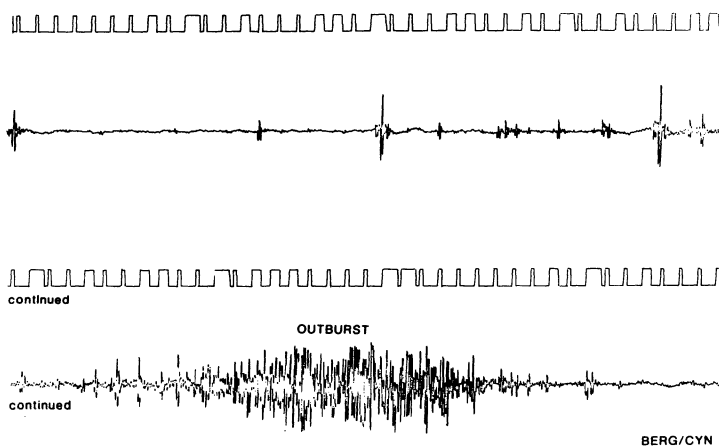


Figure 9(a)

Seismogram recorded above BV24 prior to and including the spontaneous outburst of 3rd May 1983 in BV24. Each tick on the time code represents one second.

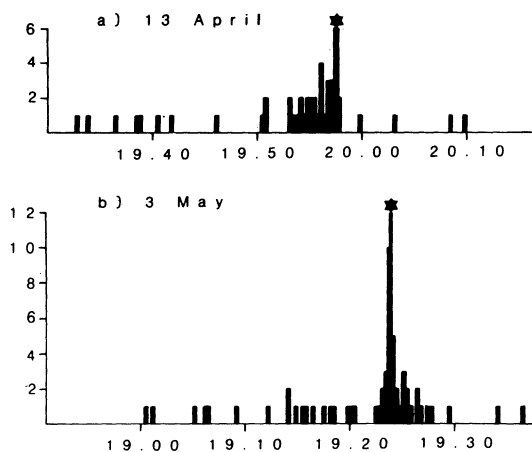


Figure 9(b)

Histograms of number of events per 20 seconds recorded above BV24 during two spontaneous outbursts in that panel (stars).

a) 13th April 1983

b) 3rd May 1983

during the minute or so prior to the outburst suggesting that this precursive activity may provide a useful predictive tool for outbursts.

DISCUSSION

22. Seismic activity has been shown to be generated by long-wall coal mining in both the North Staffordshire coalfield and at Cynheidre colliery, South Wales. Various rock failure mechanisms have been identified, including waste collapse, failure within the front abutment, subsidence induced slip on faults, and pillar collapse in old workings as they are undermined. Mining seismicity does not present an environmental problem at Cynheidre, in contrast to North Staffordshire where the seismicity has been felt extensively at the surface. The difference in the maximum magnitude of the mining seismicity generated in the two areas ($M_L = 1$ for Cynheidre, $M_L = 3.5$ for N. Staffs) can be attributed to the occurrence of seismic events with pillar failure mechanisms in the case of North Staffordshire.

23. The pillar failure events of panels 205 and 206 of the Ten Feet seam occurred predominantly within the Moss pillars when the Ten Feet face passed under the Moss seam pillar. Pillars in the Moss seam, as a result of serious extraction of this seam, would have been left with vertical stresses considerably greater than lithostatic and with lateral stress greatly reduced. Especially if these pillar cores had failed during the original mining of the Moss seam large vertical residual stresses would remain (ref. 21). While these pillars would have been stable prior to the mining of the Ten Feet seam, the superposition of the Ten Feet front abutment pressure caused renewed failure of these pillars. Failure of these pillars in compression generated the observed shear failure source mechanism. The compressional failure also enabled more strain energy to be stored compared to the tensile rock failure of smaller magnitude implosional events generated by waste collapse. The role of pillars in adjacent seams in generating mining seismicity has been reported elsewhere (ref. 22).

24. Mining seismicity, generated by pillar failure arising from the interaction of the active face with old workings, has been seen to have a magnitude, M_L as great as 3.5. By contrast, the Cynheidre data suggest that generally seismicity of magnitude <1 is associated with longwall mining in an area unaffected by previous workings. Pillar failure mechanisms therefore constitute a potential seismic hazard, particularly since the focal depth of this seismicity is shallow (800 m in the case of panels 205 and 206 North Staffordshire). Earth tremors with this type of mechanism may however be controlled or moderated by panel layouts which minimize the effects of interseam interaction.

ACKNOWLEDGEMENTS

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EARTHQUAKE ENGINEERING IN BRITAIN

However, the views expressed herein are the views of the authors and not necessarily those of the D. of E. or N.C.B.

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Discussion

DR B.O. SKIPP, Soil Mechanics Ltd
Did the list of mining induced events given include surface mining?

MR T.G.BLENKINSOP, Keele University
All the events mentioned were from underground workings.